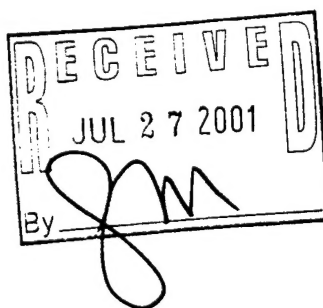


# REPORT DOCUMENTATION PAGE

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## **FINAL PROGRESS REPORT**

**Title of Project:** Sponsored Research in Radio Propagation and System Design

**Grant Number:** DAAG55-97-1-0379

**Period Covered by Report:** 01/01/97 – 12/31/99

**Name of Institution:** Virginia Polytechnic Institute and State University

**Principal Investigator:** Theodore S. Rappaport

### **Major Accomplishments:**

This report covers the three-year grant period during which ongoing research using modern propagation measurement techniques and prediction methods to create both specific and statistical ray tracing models for use in wireless communications design and simulations was performed.

MPRG's research performed in conjunction with the ARO membership in our affiliates program has produced a variety of research in propagation, signal processing, and communication system design.

This project strived to develop fundamental radio propagation modeling for indoor, urban, and rural wireless communications systems in the UHF/microwave region, with specific emphasis on spatial and temporal channel modeling. Based on extensive work conducted at MPRG, this project developed simulation tools that allow realistic propagation characteristics to be replayed on a computer, thereby providing simulation and modeling tools for modem design, adaptive antenna research, and position location algorithms. Measurement hardware was also created and used to conduct field measurements that included angle of arrival information on multipath components.

Research highlights were captured in technical reports and papers subsequently copied and delivered to MPRG industrial affiliate members, including ARO, and are also available on the "affiliate webpage" at the MPRG web site [www.mprg.org](http://www.mprg.org). One publication of particular interest is a paper entitled "An Antenna Specific Site Modeling Tool for Interactive Computation of Coverage Regions for Indoor Wireless Communications" that presents an interactive software system that can aid transceiver placement by using simple path-loss models to predict coverage for transceivers within a graphical floor plan. Another paper, "Advanced Site-Specific Propagation Prediction Techniques" reports on measuring and modeling continuous wave (CW) local-area path loss, demonstrating the validity of the original models and techniques presented; it also develops deterministic propagation prediction techniques and presents a new 3D ray launching method that improves upon many of the existing ray tracing algorithms. The report entitled "Radio Wave Propagation Study at 38 GHz" presents the results of an extensive point-to-point radio wave propagation study, with measurements taken during a

variety of weather events and provides good insight into multipath and reflectivity. Another report, "Peer-to-Peer Wideband Outdoor Track Measurements at 1.8 GHz: The ITT Project Report," describes an extensive wideband outdoor channel measurement campaign, details the measured channel power-delay profiles and radio channel measurements, and presents new research directions of promise in mobile radio channel research with measured data playing an essential role in the development of the Handheld Mobile Terminal (HMT). Also, the paper entitled "Antenna Array Systems: Propagation and Performance" reports on signal propagation modeling for antenna array systems and on its relationship to the performance of these systems.

Signal processing research achievements included the new architectures in software radio design, new adaptive array algorithms that are blind and exploit temporal and spatial diversity, and new reduced complexity turbo coding algorithms. Communication system design included network planning issues in using smart antennas and system designs to implement smart transmit antennas with feedback.

Enclosed with this final progress report are three volumes with abstracts that cover research projects for 1997, 1998, and 1999, along with a list of publications produced by the group during this three-year period.

**Technology Transfer:** None directly related to ARO sponsorship.

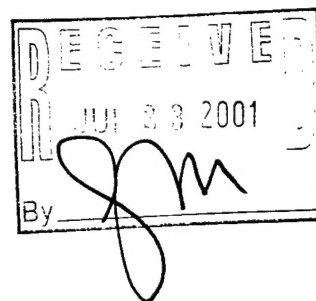


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AND STATE UNIVERSITY

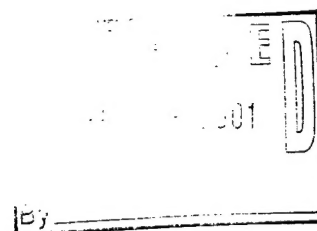
**The Bradley Department of Electrical and  
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Mobile and Portable Radio Research Group  
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Blacksburg, Virginia 24061  
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July 18, 2001



Ms. Mary N. Jackson  
Army Research Office  
ATTN: AMSRL-RO-RI (Technical Reports)  
P.O. Box 12211  
Research Triangle Park, NC 27709-2211



Re: DAAG55-97-1-0379

Dear Ms. Jackson:

Enclosed is the final progress report for Grant Number DAAG55-97-1-0379 for the grant period January 1, 1997 – December 31, 1999. Also enclosed is a disk with the files in MS Word format.

Please let me know if you need additional information.

Sincerely,

Dr. Jeffrey H. Reed  
Director, Mobile & Portable Radio Research Group

Enclosures    Final Progress Report  
                  1997, 1998, 1999 Project Abstracts  
                  1997, 1998, 1999 Publication Lists  
                  Disk with all files

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VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY

**MPRG**

MOBILE & PORTABLE RADIO RESEARCH GROUP

# **PROJECT ABSTRACTS**

**1997**

**for the**

**MOBILE & PORTABLE RADIO RESEARCH GROUP**

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Virginia Polytechnic Institute and State University

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## ***Bell South Parasitic Cellular***

**\* Sponsor**  
**Bell South Wireless, Inc.**

**Principal Investigator**  
**Theodore S. Rappaport**

**Student**  
**Bob Brickhouse**

This project was the subject of Bob Brickhouse's M.S. Thesis, which he defended in September 1995. The objective of this study was to provide an analysis to determine the frequency reuse possible between in-building and outside cellular systems. This work used real world cellular planning techniques to estimate the capacity and growth of cellular systems over a six (6) year period. Furthermore, the study estimated what the level of in-building interference is within a building located in the urban core of a top-ten cellular market, as the outdoor cellular system grows over time.

To simulate the growth of cellular users within a city, Bell South provided realistic marketing data and technical information for over 50 cell sites. We used the physical locations and actual channel assignment schemes of each cell site, along with the antenna and transmitter parameters, to determine the present day capacity and coverage of the cellular system. Then, using actual field measurements of building penetration and radio path loss within an urban environment, we measured the current number of channels within a large building that can be reused by indoor (parasitic) cellular systems. The number of available channels are determined as a function of floor level in the building, as well as the received power threshold (from 80 dBm to 95 dBm).

Using the propagation model and simulated customer growth rates of 40% within the urban core and 25% outside of the core, we predicted the state of the cellular system design at 3 month intervals. Cells were split whenever offered traffic reaches 5% blocking probability, and cell splits are made using the Lee model of a 4:1 split. Frequency assignments were based on an algorithm which selects the maximum C/I on the forward link. A simulation code was written which models a growing cellular system for the purpose of analyzing the effect that a growing cellular system will have on in-building frequency reuse. Future in-building frequency reuse was predicted in three month intervals for a time period of six years based on the results of the simulation code.

## ***Development of Software-Based Receivers***

**\*Sponsor  
Texas Instruments**

**Principal Investigators  
Jeffrey H. Reed, Brian D. Woerner**

**Students  
Brian Fox, George Aliftiras**

With the proliferation of wireless communications standards, cellular telephones and personal communications will be required to cope with an increasingly complex environment. In order to meet customer demands for roaming and interoperability, there will be a need for dual-mode and multimode handsets which are compatible with a variety of transmission standards. The availability of high-speed, programmable DSP chips is a key technology which may enable the development of such receivers.

This project focuses specifically on the design of a software-based receiver for multiple cellular standards, and focuses on a number of key issues in that design. These issues include where the line between the RF and baseband DSP processing should be drawn, and the possible use of Sigma-Delta analog to digital converters as a means of simultaneously supporting narrowband systems with high resolution requirements and wideband systems with relatively low resolution requirements. Simulation results indicate that CDMA systems require only a few bits of analog-to-digital converter resolution for acceptable performance.

## ***A Novel Curriculum for Wireless Communications***

**\*Sponsor  
National Science Foundation**

**Principal Investigators  
Theodore S. Rappaport, William H. Tranter, Jeffrey H. Reed, Brian D. Woerner**

**Students  
Donna Krizman, Nisith Tripathi, Andrew Park, Jamel Lynch**

This project is the result of a collaborative effort between Virginia Tech and the University of Missouri - Rolla. This proposal aims to meet the escalating needs of the wireless communications industry for trained personnel by developing a novel curriculum in wireless communications techniques which will be implemented at the senior and first year graduate level.

Under this project we will develop a three course sequence in wireless communications. Course 1, to be taught during the first semester of the senior year, will introduce students to the fundamentals of Digital and Analog Wireless Communications. This course will feature fundamental material on modulation, and will emphasize the design of wireless system components using Matlab simulation modules which will allow the students to "see" and "hear" the results of their design choices. This course also aims to expose students to the entrepreneurial flavor of the wireless industry through open-ended design projects and an emphasis on oral and written presentation. Course 2 will be a hardware based course in the DSP implementation of wireless systems. During the course of the semester, each team of students will construct a complete wireless modem following a set of pre-designed laboratory units. This course will be offered during the second semester of the senior year. Course 3 is a new course on the Simulation of Communication Systems, and will be offered at the graduate level. This course will cover the key aspects of simulation as a design paradigm for wireless systems. It is anticipated that a new textbook will be developed as part of this course.

The materials developed for this novel wireless curriculum will be made available to other educators throughout the nation. Progress will be updated regularly on a worldwide web page: "<http://www.ee.vt.edu/mprg/nsf/nsf.html>"

# ***Development of a High-Capacity Low-Power Spread-Spectrum Modem***

Sponsor

**Advanced Research Projects Agency (ARPA)**

Principal Investigators

**Theodore S. Rappaport, Jeffrey H. Reed, Brian D. Woerner, Peter Athanas**

Students

**Joe Liberti, Jeff Laster, Bill Khun, Nevena Zecevic, Mike Buehrer, Rick Cameron, Ashish Kaul, Zhigang Rong, Milap Majmundar, Nitin Manglavedhe, Steve Nicoloso, Paul Petrus, Neiyer Correal, David Covert, Francis Dominique**

Because the demand for information appears to be insatiable, the key performance criteria for future wireless systems will be the ability to make efficient use of the available frequency spectrum. The current industry consensus is that CDMA systems based on spread-spectrum technology can be highly efficient. This project aims to further improve the efficiency of a CDMA system by incorporating four key technologies:

- 1) Interference rejection techniques allow a CDMA system to support a greater number of users in a given location. Both adaptive interference cancellation and time-dependent adaptive filtering (TDAF) will be investigated as techniques to reject interference. Preliminary simulations indicate that both these techniques are capable of increasing system capacity by up to a factor of three. Adaptive interference cancellation may be employed at the base station, while TDAF may be better suited for use at the mobile receiver.
- 2) Adaptive antenna technology reduces interference by allowing a receiver to steer an antenna array towards the desired user. Preliminary simulation and analysis indicate that significant capacity improvements are possible if adaptive antenna technology is employed at the base station. An adaptive antenna testbed will be built and a variety of beam steering algorithms will be investigated. Channel models useful for evaluating the adaptive array are being created.
- 3) Intelligent System Design uses site-specific propagation prediction to predict the impulse response and angles of arrival of multipath in a mobile system. The prediction models use terrain and building databases, along with ray tracing techniques, to develop adaptive array algorithms and determine base station placements. Preliminary results show how site-specific models corroborate experimental angle of arrival measurements for a 6 element adaptive array.
- 4) Signal processing technology allows high performance at low powers by striking a middle ground between application specific hardware and general purpose computing architectures. Preliminary results indicate that order of magnitude speed improvements over conventional DSP-processors are possible.

The end result of this three year project will be the construction of a prototype receiver which will incorporate these four technologies.

## ***Combined Coding and Modulation for CDMA***

**\* Sponsor  
National Science Foundation**

**Principal Investigator  
Brian D. Woerner**

**Students  
Young Min Kim, Ning Yang, Xu Lin**

This project focused on the development of combined coding and modulation or "trellis coding" techniques for wireless communication applications. Within the scope of the project, a number of novel approaches were investigated.

Young Min Kim investigated a technique for using trellis codes with CDMA systems by using the output of the error correction encoder to select the signature sequence which is used to transmit a particular symbol. Although previous research showed that trellis codes were ineffective for CDMA, this research demonstrated significant performance improvements were possible when the error correction code was combined with the choice of both modulation and spreading codes. Analysis and simulation showed that capacity improvements of up to 20% were possible for both AWGN and fading channels when compared with the best known conventional codes of equivalent complexity.

Xu Lin investigated the application of trellis coding techniques to narrowband wireless systems. While previous trellis coding research has focused almost exclusively on coherent modulation schemes, Xu Lin's research focused on noncoherent modulation techniques. In particular, this research investigated the use of trellis codes with permutation modulation. Unlike conventional M-ary FSK modulation in which just one of M possible tones is transmitted, permutation modulation employs several simultaneous tones out of the M possible tones, resulting in greater spectral efficiency. Permutation modulation also provides a rich distance structure which can be exploited by a properly chosen trellis code. Xu Lin's MS Thesis, completed in May 1996, demonstrated that it is possible to achieve improved combinations of energy and spectral efficiency using trellis coding permutation modulation. This research has possible application to new high capacity paging standards.

# ***Curriculum Innovation for Simulation and Design of Wireless Communications Systems***

Sponsor  
**National Science Foundation**

Principal Investigators  
**Theodore S. Rappaport, William H. Tranter, Brian D. Woerner, Jeffrey, H. Reed**

Students  
**Donna Krizman, Andrew Park**

This project teams electrical engineering faculty from Virginia Tech's Mobile and Portable Radio Research Group and from the University of Missouri-Rolla to develop an innovated communications curriculum which integrates current research from the wireless communications field. The principal investigators are able to draw on research expertise in the fields of radio signal propagation modeling, simulation of wireless communications systems, and implementation of novel digital signal processing techniques to improve the performance, cost and spectral efficiency of wireless modems.

A three course sequence is proposed to integrate wireless communication concepts into the electrical engineering curriculum at the senior undergraduate and first year graduate levels. Course 1 introduces digital and analog communication system design from a wireless perspective. Course 2 presents hardware-based design experience on the implementation of wireless modems using modern digital signal processing technology. Course 3 is a graduate course covering simulation concepts for wireless communication systems. All three courses emphasize design and the combination of fundamental concepts with current industry practice, while attempting to convey to the student a portion of the entrepreneurial spirit which permeates today's wireless industry.

The course development for this project will be incorporated into the curriculum at both Virginia Tech and University of Missouri-Rolla. Instructional materials developed for this project will be disseminated throughout the academic community in the form of textbooks, software modules, "Design Studies", a video tape series, and course notes to be made available through World Wide Web site: "<http://www.ee.vt.edu/mprg/nsf/nsf.html>".

***Use of Topographic Maps with Building Information to Determine Antenna Placements and GPS Satellite Coverage for Radio Detection and Tracking in Urban Environments***

Sponsor

**Office of National Drug Control Policy (ONDCP)**

Principal Investigator

**Theodore S. Rappaport**

Students \*

**Keith Blankenship, Kevin Krizman, Bill Newhall, Neal Patwari, Roger Skidmore**

The ONDCP project currently supports a number of students and staff members, and is a three year project to develop site specific propagation prediction (SISP) models within MPRG. Current work involves three phases: measurement system development; propagation model development; and software ray tracing and modeling development. Now, it is possible for any type of propagation measurement to be entered into SISP by using a generalized data format (GDF). Building and terrain databases are now being standardized so that present and future students can develop propagation models that are independent of the specific data base used (this is a departure from past work in which the propagation models were tied to the particular way the data base was implemented). This new approach will provide a very flexible tool that enables propagation modelers to develop and build models. The models may be used for polarization studies, array algorithm work, emergency position location, and PCS deployment studies.

The measurement system currently uses both CW and wideband (SS) sounding techniques and works at 910 MHz (20 MHz BW) and 1910 MHz (50 to 200 MHz BW). Currently, Bill Newhall, is upfitting the system to 6 GHz, and is building high gain antennas that will support 10 degree angle of arrival measurements at 6 GHz. As part of the ONDCP, students will be making measurements at these 3 bands before year end and will use the data to improve the ray tracing models. We hope to build 18 GHz and 28 GHz systems within the next year, and this is a focus of graduate students Bill Newhall and Keith Blankenship. These measurement tools promise to be the core of popular commercial measurement products of the future.



# ***Practical Considerations in the Design of Cellular Digital Packet Data (CDPD) Equipment***

Sponsor  
**MPRG Industrial Affiliates Program**

Principal Investigator  
**Theodore S. Rappaport**

Student  
**Gregory D. Bump**

This project was the subject of Greg Bump's M.S. Thesis, which he defended in September 1995. It documents the development of some of the first commercially available CDPD test and measurement equipment. It provides a general overview of the operation of the CDPD network and an in-depth analysis of the major technical challenges in the development of CDPD equipment; Gaussian Filtered Minimum Shift Keying (GMSK) and Reed-Solomon error correction codes. It also presents fundamental information required to successfully implement CDPD base station or mobile equipment. This information includes an introduction to the operation of data networks, a discussion of Gaussian Filtered Minimum Shift Keying (GMSK), and a detailed analysis of Reed-Solomon error correction codes.

A result of this research was the development of a CDPD AirLink analyzer for *TSR Technologies*, which was later acquired by *Grayson Electronics Company*, who has since been contracted by *Hewlett Packard* to provide CDPD protocol testing capabilities for the HP-8920 series of test analyzers.

## ***Analysis and Simulation of Packet Reservation Multiple Access (PRMA)***

\* Sponsor

**MPRG Industrial Affiliates Program**

Principal Investigator

**Theodore S. Rappaport**

Student

**Varun Kapoor**

This project was the subject of Varun Kapoor's M.S. Thesis, which was defended in May 1995. The project analyzed a multiple access scheme proposed by Goodman et. Al, known as the *Packet Reservation Multiple Access* (PMRA). This scheme is a combination of TDMA and the Slotted ALOHA protocol, which allows a group of spatially dispersed terminals to transmit packet voice and low bit rate data over a common channel to a central base station. The key feature of this protocol is to use a request on user transmitted data to gain access to the radio channel. PRMA is basically a scheme designed for speech where data information can be transmitted when no speech terminal is contending for a reservation on the channel. When a speech terminal succeeds in gaining access, subsequent time slots are reserved for its uncontested transmission. To take advantage of the discontinuous speech information, PRMA utilizes a *voice activity detector* to increase channel capacity. This project evaluated the performance of PRMA access protocol, and also described an attempt to implement a PMRA based system in BONEs.

# *Analysis of CDMA Cellular Radio Systems Employing Adaptive Antennas*

\* Sponsor

**Advanced Research Projects Agency (ARPA)**

Principal Investigator

**Theodore S. Rappaport**

Student

**Joe Liberti**

This project was the subject of Joe Liberti's Doctoral Thesis, which he defended in September 1995 and is part of the Global Mobile Communications Project (GloMo). The project investigated the performance of Code Division Multiple Access (CDMA) cellular communication systems employing adaptive antennas at the base station. First, a simple analysis was presented which showed that significant improvements in performance can be obtained by using directional antennas in the mobile-to-base station link of CDMA cellular radio systems. Next, steps were taken to improve the analysis of CDMA systems employing adaptive antennas. The first step in improving the analysis was to develop new analytical bit error rate estimation tools which were much more accurate than previous expressions when power control is imperfect, when intercell interference degrades system performance, and when directional antennas are used at one end of the CDMA radio link. These expressions were further extended to accommodate multipath radio channels when omni-directional antennas, fixed directional antennas, or adaptive antennas are applied at either end of the link. This project also developed a channel model which may be used to simulate the direction-of-arrival (DOA) as well as the time-of-arrival (TOA) and power level of multipath components. These analysis techniques were used to develop a simulation framework which can model the performance of CDMA systems, incorporating the effects of the multipath channel, optimal adaptive antenna arrays, and more accurate bit error rate expressions.

## ***Direction of Arrival Estimation Using Antenna Arrays***

\* Sponsor

**Advanced Research Projects Agency (ARPA)**

Principal Investigator

**Theodore S. Rappaport**

Student

**Rias Muhamed**

This project was the subject of Rias Muhamed's M.S. Thesis, which he defended in January 1996. The objective of the project was to design, build and evaluate a direction-of-arrival measurement system using an antenna array operating at 2050 MHz. The first phase of the project was an extensive study of various high resolution DOA estimation algorithms. The algorithms studied included subspace-based techniques such as the MUSIC (Multiple Signal Classification) and ESPRIT (Estimation of Signal Parameters via Rotational Invariance) algorithms, and the integrated approaches which combine property restoral-based techniques such as the Iterative Least Squares Projection-based Constant Modulus Algorithm (ILSP-CMA) with subspace-based techniques. All these algorithms were simulated in MATLAB and their performance under different conditions was tested and compared. In the second phase of the project, a six element uniformly spaced linear array receiver was built. Three Ariel DSP-96 boards on the Motorola DSP96002 were used to simultaneously sample, collect, and store data from each of the array elements. The data collected by the DSP boards was processed off-line to estimate the directions of arrival. Several experiments were conducted to test the functioning of the system under various conditions, and demonstrate the performance of different algorithms. A surprising and extremely useful result was that simple ray tracing was accurately able to reproduce the measured algorithm performance in the MPRG parking lot. Measured and simulated results were identical when ray tracing channel models were applied to the simulation code, and demonstrated the potential value of site specific ray tracing channel models in research and development.

## ***Indoor Wireless System Planning and Simulation***

\* Sponsor

**National Science Foundation Presidential Faculty Fellow Award**

Principal Investigator

**Theodore S. Rappaport**

Students

**Roger Skidmore, Nitin Bhat**

This project is the subject of Roger Skidmore's M.S. Thesis and is concerned with expanding and improving the Site Modeling Tool (SMT), a comprehensive software package for planning and simulating any type of indoor wireless system. The goal of the SMT is to provide the means for the quick and easy deployment of indoor wireless systems. As a result of this project, MPRG has recently released SMT *Plus*<sup>TM</sup> 1.0 and an accompanying software tool known as *SiteBuilder*<sup>TM</sup>.

The incorporation of actual measurements into the SMT system is the future goal of this project. By displaying measured data points within the building floor plan, either as single points or by doing a curve to fit the entered data, SMT's visual feedback will offer the means to integrate measurements into the system. By incorporating knowledge of the actual measured signal strengths within a building, the accuracy of SMT can be further increased. Graduate student Nitin Bhat is currently developing techniques which will enable the user to apply any type of antenna pattern, including user defined patterns, to any system being developed. The ability to accommodate distributed antennas will also be a subject of study.

# ***Simulation and Implementation of Adaptive Array Algorithms in Multipath Fading Channels***

Sponsor

**Advanced Research Projects Agency (ARPA)**

Principal Investigator

**Theodore S. Rappaport**

Student

**Zhigang Rong**

In wireless communications systems, employing an adaptive array, the signals received by multiple antennas are weighted and combined to suppress interference, combat signal fading and thus increase system capacity. There are many adaptive algorithms that can be used to update the combining weights of adaptive antenna arrays. Most of them can be categorized into two classes according to whether a training signal is used or not. One class of these algorithms is the non-blind adaptive algorithm in which a training signal is used. Another technique is to use a blind adaptive algorithm which does not require a training signal. This research investigates the performance of different algorithms in multipath fading channels. First, a simulation testbed will be created using MATLAB to compare the performance of several algorithms in a Code Division Multiple Access (CDMA) system. The candidate algorithms for the simulation are Multi-target Constant Modulus Algorithm (CMA), Beam-Space CMA and other hybrid algorithms. These algorithms are compared in terms of computational efficiency, convergence speed, implementation architecture, and ability of resistance to interfaces under different situations (i.e. overloaded or underloaded). In the simulation, various channel models such as SIRCIM, SMRCIM, and Ray Tracing models will also be used and the results for different models will be compared. Based on the simulation results, one or two of the algorithms will be chosen to implement on the DSP board.

## ***Presidential Faculty Fellow Award***

\* Sponsor  
**National Science Foundation**

Principal Investigator  
**Theodore S. Rappaport**

This project provides funding for Dr. Rappaport, his secretary, and up to 4 students to design and develop teaching materials for the wireless communications industry, and simulation tools for research and design of wireless systems. Funding is scheduled to last until September 1997.

This grant is to develop new teaching tools for the wireless industry and academia. Several MPRG research tools, such as SIRCIM, SMRCIM, BERSIM, and SMT, have been developed and improved from this grant. These tools are poised for commercialization and have been purchased through the university by over 100 companies and universities.

This grant has also been used to develop a 10 lecture short course for industry in the area of mobile communications, and has recently been used by Dr. Rappaport to prepare an improved set of lecture notes for EE 6644, the graduate course at Virginia Tech *entitled Cellular Radio and Personal Communications*. This grant has also enabled him to prepare two collections of selected readings published by the IEEE Press. The first book, entitled Cellular Radio and Personal Communications: Selected Readings, was published in 1995 and contains 40 key papers in the following areas of wireless personal communications: cell design, propagation, modulation, channel coding and diversity, speech coding, multiple access techniques, networking, and world-wide standards. The second book, entitled Cellular Radio and Personal Communications: Advanced Selected Readings, is at the publisher and will be marketed in the spring of 1996.

The PFF grant has also allowed Dr. Rappaport to develop a self-study course for the IEEE, which will serve as a useful industry guide. A full-fledged textbook, entitled Wireless Communications: Principles and Practice, is the industry's first text for practicing engineers, and seniors and first year graduate students. The text was published by Prentice Hall in late 1995 and was used by over 30 universities after it's release. Another text, Simulation of Modern Communications Systems, is being prepared by Dr. Rappaport with Bill Tranter and Kurt Kosbar of the University of Missouri, Rolla, and the text CDMA and Adaptive Antennas has been prepared by Dr. Joe Liberti and Dr. Rappaport.

## ***Digital Receiver Design for ITS Applications***

**Sponsor**

**Federal Highway Administration ITS Research Center of Excellence**

**Principal Investigators**

**Brian D. Woerner, Jeffrey H. Reed**

**Students**

**George Mizusawa, Nitin Mangalvedhe**

This work is part of MPRG's continuing collaboration with Virginia Tech's Intelligent Transportation Systems (ITS) Research Center of Excellence, which is supported by the Federal Highway Administration. Rather than construct an entirely new communications infrastructure specifically for ITS, we believe that future ITS systems will make use of the existing wireless communications infrastructure, including cellular and PCS. Previous years' work on this project has focused on the development of dual-mode receivers which would support ubiquitous communication with outside wireless networks.

This year's research has focused on incorporating position location capability technology into the wireless infrastructure. This capability is required for a large number of ITS applications including emergency response, traffic management, navigation, and traveller information systems. Because of ongoing FCC actions, it also appears likely that wireless service providers will be required to incorporate position location capability into Enhanced 911 service within the next several years.

We have focused on infrastructure-based position location techniques which will allow the service providers to locate a mobile user without significant changes to existing mobile handsets. We have thoroughly surveyed existing research and technology and are now investigating both time-difference of arrival (TDOA) and angle of arrival (AOA) techniques. Of particular interest is the performance of these techniques in urban multipath environments.



## ***Evaluation of E911/Mayday Service for the I-95 Corridor***

**\* Sponsor  
I-95 Corridor Coalition**

**Principal Investigators  
Ray Pethtel, Jeff Reed, Bob James, Brian Woerner**

**Students  
Don Breslin, Alan Alexander, George Mizusawa**

This project is undertaken jointly with Virginia Tech's Center for Transportation Research. The I-95 Corridor Coalition is a consortium of state and local transportation authorities along the Mid-Atlantic and Eastern seaboard. This consortium is interested in developing a low-cost solution to providing emergency "Mayday" service for vehicles throughout the I-95 corridor. The project, which runs through March 1997, will consist of surveying available technology and then formulating plans for an operational field test of Mayday technology in the I-95 corridor.

A number of solutions to providing Mayday service are available. One low-tech solution is the widespread-availability of call-boxes throughout the I-95 corridor. While this solution is inexpensive, it is inconvenient and requires travellers to leave their vehicles which may present a safety hazard in itself.

A second possible solution is to have a Mayday communications device on-board the vehicle. This will likely be a cellular telephone or personal communications device. This solution is more expensive, and it will be years before near-universal coverage is attained. However, in-vehicle communications would make more accurate position location possible. Position location could either be through a passive determination by the wireless infrastructure, or it could be through a Global Positioning System (GPS) receiver located on board the vehicle.

## ***Interference Mitigation in FM Systems***

### **\*Sponsors**

**SAIC, Motorola, MPRG Affiliates, Center for Wireless Telecommunications**

### **Principal Investigator**

**Jeffrey H. Reed**

### **Students**

**Rong He, Khawar Khan, Matt Welborn, Wen-Chun Ting, Jeff Laster**

The goal of this project is to create interference robust demodulators of AMPS, NAMPS, and GSM signals. The expected result is an increase in system capacity, system coverage, voice quality, and network reliability.

The approaches investigated in this study include:

- \* Time-Dependent Adaptive Filters
- \* Neural Network Filters
- \* Model-based Demodulators
- \* Diversity through Alternative Demodulators

Time-dependent filtering has been studied in greatest detail. The technique has shown to provide much better voice quality for AMPS and NAMPS and is power efficient. Capacity is significantly improved by using the technique. Computational requirements do not preclude its use at the handset.

The model-based demodulation and neural network filtering have shown to be effective in reducing interference for GSM, AMPS, and NAMPS signals. Some forms of the model-based demodulator are feasible for implementation at the handset, but further work is needed to reduce the computational count.

Preliminary results in creating diversity through alternative demodulators have been very promising for reducing the impact of interference and multipath distortion for GSM signals.

## ***Performance Evaluation of DECT in Different Propagation Environments***

**\*Sponsor  
National Semiconductor**

**Principal Investigator  
Jeffrey H. Reed**

**Student  
Kevin Saldanha**

The Digital European Cordless Telecommunications standard (DECT) defines a high performance wireless communications system suitable for the two way transfer of voice, data, and video information. The standard has been tested in low dispersion indoor radio channels but tests of a commercial implementation in typical indoor/outdoor radio channels are highly desirable. National Semiconductor Corporation (NSC) produces a state-of-the-art chip set which implements the DECT standard. The chip set performs well in static tests, but NSC desires a performance evaluation of its DECT chip set in an actual mobile environment with the added impairments of adjacent and co-channel interference (ACI and CCI).

To accomplish this task, simulation and channel measurements with actual data transmission using the NSC DECT transceiver will be used. A measurement will consist of a channel sounding followed by the transmission of DECT test message. Channel sounding will be done using a sliding correlator measurement system. After channel sounding, the DECT transmitter is switched on to the sounder antenna, and a test message will be sent to the DECT receiver. The received message is then recorded and stored. This test will be repeated for lower signal levels by placing an attenuator in the test transmitter output and retransmitting the message. A test message of 1 million bits will be used to insure a valid BER measurement. A second DECT transmitter will be combined through an attenuator with the test DECT transmitter and various levels of CCI and ACI can be simulated by adjusting the attenuators in the transmitter outputs. The test message can be transmitted through CCI and ACI.

SPW will be used to process the actual test message through a channel which is described by the measured power delay profile (PDP). The BER of the received message will then be compared with the BER of the simulation. The predicted performance of the channel can be compared with the actual performance.

Polarization diversity in the hand set is proposed as a way to improve DECT performance. Simple dual polarized antennas will be constructed and used with the DECT measurement program. The performance of DECT systems with and without polarization diversity will be compared.

## ***Simulation Evaluation of CDPD***

**Sponsor**  
**MPRG Industrial Affiliates Program**

**Principal Investigator**  
**Jeffrey H. Reed**

**Student**  
**Scott Elson**

Cellular Digital Packet Data (CDPD) is becoming a widely used mechanism for transmitting data over the cellular network. It has been selected in the two national intelligent transportation studies as the primary communication system for future automotive data communications.

Our work focuses on simulating the link-level performance of this standard under a variety of interference and multipath conditions. The errors in the signal structure are examined to determine potential weakness in the signal format. Alternative demodulators are examined for use with CDPD in different channel environments.

# ***Neural Net and Fuzzy Logic Approaches to Handoffs in Cellular Systems***

**\*Sponsor**

**MPRG Industrial Affiliates Program**

**Principal Investigators**

**Jeffrey H. Reed and Hugh VanLandingham**

**Student**

**Nishith Tripathi**

The process of handoff assumes more and more importances as the cell sizes become smaller and smaller. High performance handoff algorithms can lead to a better cellular system in terms of the quality of service and the network capacity. Since handoff problem can be viewed as a pattern classification problem or an optimization problem, adaptive, nonlinear and intelligent (i.e., capable of learning) tools such as neural networks and fuzzy logic can be used to develop high performance handoff algorithm.

The following work has been accomplished:

- A comprehensive literature search has been done on handoff techniques, and many relevant papers have been obtained
- A general report on handoff and related issues has been prepared
- Some simulation models for analysis of handoff algorithms has been prepared
- Techniques that perform a tradeoff between the interference caused to other users and the number of handoffs has been developed using a neural network and a fuzzy logic system.

VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY

**MPRG**

MOBILE & PORTABLE RADIO RESEARCH GROUP

# **PROJECT ABSTRACTS**

**1998**

**for the**

**MOBILE & PORTABLE RADIO RESEARCH GROUP**

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**Virginia Polytechnic Institute and State University**

**432 NEB, Mail Code 0350**

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## ***RF Multipath Channel Measurement and Study at 38 GHz***

Sponsored by

***Hughes Networks Systems and HRL Laboratories***

Principal Investigators

***T. S. Rappaport***

Student Researcher:

***H. Xu***

Project Duration:

***March 1998 - December 1999***

The design of a wideband digital communication system requires a quantitative understanding of the RF channel in which it is expected to operate. In particular, for a high data rate transmission system at 38 GHz, not only is the multipath information at an instantaneous time or on a time average basis necessary, but the rate of change of the channel with time is also highly desirable. Further, since the wavelength is only 7.9 millimeters long at this frequency, one must consider different weather conditions such as snow and rain effects, in the system design.

With this in mind, MPRG proposes to conduct wideband measurements for Hughes Network Systems (HNS) in the 38 GHz and 60 GHz ranges. These measurements will capture the time dispersive nature of the channel for a number of weather related scenarios. Our goal is to provide quality channel measurement data that will allow HNS to determine the polarization diversity and equalization requirements for their point to multipoint communications systems in and around buildings and to understand the range of time delays and amplitude variations associated with man-made objects and weather events on 38 GHz and 60 GHz links.

# ***Turbine Engine Control Using MEMS for Reduction of High Cycle Fatigue***

Sponsored by  
***Air Force Office of Scientific Research***

Principal Investigator  
***Theodore S. Rappaport***

Student Researchers  
***Christos Kontogeorgakis, Mujahid Ali***

Project Duration  
***July 1997 – June 2000***

A research program is proposed to use the emerging technology of micro-electro-mechanical-systems (MEMS) in gas turbine engines. Since August 1998, the focus of the research is on the design and modeling of wireless passive microsensors as well as the estimation of signal strength coverage within a Boeing Aircraft. For the first part of the research, the use of surface acoustic wave (SAW) devices, as sensors as well as wireless platforms to accommodate MEMS sensors, was investigated. It has been demonstrated that SAW devices can operate as wireless passive identification tags. Based on this principle, an RF equivalent model is developed using the HP EEsof SERIES IV and ADS software tools. This enables us to design and test various sensor architectures in a fast and cost effective way. For the second part of the research, the simulation of a Boeing Aircraft, a 3D model of a Boeing 747 in Autocad®, was used to predict the received signal strength indicator (RSSI) coverage using the SitePlanner™ software tool. The Boeing model was placed in the Building Database Manipulator (BDM™) to generate a 3D site-specific model of the plane. BDM categorizes similar attributes of the plane into different partitions. Each partition is then assigned a certain dB loss value. This was done so that Infielder™ will have all the necessary information for it to predict the RSSI coverage. Two transmitters were placed on the Boeing 747's engines radiating at 2.4 GHz and 5.2 GHz frequencies respectively.



## ***Presidential Faculty Fellowship***

*Sponsored by*  
***National Science Foundation***

Principal Investigators  
***T. S. Rappaport***

Student Researchers  
***G. Durgin, H. Xu, R. Skidmore, S. Mahmud, B. Walsh, W. Rios***

Project Duration  
***March 1996 – February 1999***

A thorough understanding of the radio propagation characteristics and appropriate channel modeling techniques are vital to the successful deployment of wireless networks. Contemporary wireless networks are designed relying on exhaustive propagation measurements and it is not uncommon to avoid "dead zones" by overdesigning. This makes the network more expensive and inefficient operationally and spectrally. Research at Virginia Tech's Mobile and Portable Radio Research Group (MPRG) has developed promising propagation modeling techniques that use digitized building databases with topographic maps. The resulting propagation models provide prediction accuracies of signal strength, coverage, and multipath spread that are better than those reported in the literature. For example, the new modeling techniques provide signal strength predictions that are consistently within 5 dB of the actual local average at every point within the engineering complex of a college campus, and the models reliably predict dead zones due to the shadows of different buildings. Recently, models and measurement techniques for wireless local area networks (LANs) have been included in the research.

***Professional Production Services for Technical Reference Books at  
Prentice Hall***

\*  
Sponsored by  
***Prentice Hall PTR***

Principal Investigator  
***T. S. Rappaport***

Research Associates  
***A. Scharnhorst***

Project Duration  
***August 1998 – July 1999***

Prentice Hall, a world-leading publisher of technical books, seeks the expertise and services of Virginia Tech's Mobile and Portable Radio Research Group. As Prentice Hall attempts to attract world-leading authors and develop leading educational and technical books, it wishes to team with MPRG in the development of potential markets and a more prominent presence in the telecommunications field. By associating with Virginia Tech's MPRG and its capable technical editing staff, Prentice Hall could have an advantage in attracting potential authors in the field of wireless and telecommunications.

# ***Measurement-Based Spatial-Temporal Channel Modeling for Handheld Multi-media***

Sponsored by  
***ITT Industries***

Principal Investigator  
***T. S. Rappaport***

Student Researchers  
***N. Patwari***

Project Duration  
***May 1998 – December 1998***

The use of cellular phones and pagers today has become a pervasive element of our culture. We expect to be able to contact anyone, anywhere. Our 'cellular phone culture' accepts no excuses for lack of coverage in a particular area, or call blocking due to capacity limits. New peer-to-peer systems will follow in the tradition of the walkie-talkie, the CB radio, and the two-way radio. Peer-to-peer radios will communicate directly with one another without the need for a base station. This may be a feature on a cellular phone that can re-direct traffic away from the base station. Or it may enable a group of users to enter an area without a base station and still be able to communicate with one another. This report studies the peer-to-peer radio channel to aid in the design and simulation of new high bit-rate peer-to-peer radios. The use of low antennas at both ends of the link and the wide bandwidth make the peer-to-peer channel particularly susceptible to time and angle dispersion. New measurements are necessary to characterize this dispersion.

In this extensive outdoor propagation study, low antenna heights of 1.7 m are used at both the transmitter and the receiver to measure over 3500 wideband power-delay profiles (PDPs) of the channel for a peer-to-peer communications system. Rural and urban areas are studied in 22 different transmitter-receiver links. The results are used to characterize the narrowband path loss, mean delay, root-mean-square (RMS) delay spread, and timing jitter of the peer-to-peer wideband channel. Small-scale fading characteristics are measured in detail by measuring and analyzing 160 PDPs within each local area. This project shows the measurement setup for the calculation of fading rate variance and angular spread and reports the first attempt to calculate angular spread from track power measurements. Finally, a new measurement-based channel model is introduced for simulation of wideband fading processes in high-bit rate peer-to-peer radio communication systems.

## ***Transmission of Video over a Wireless Channel***

Sponsored by  
***MPRG Affiliates Program***

Principal Investigators  
***Jeffrey H. Reed***

Student Researchers  
***P. Max Robert***

Project Duration  
***1997-1999***

Given the trend toward high speed and high capacity in today's networks, the availability of new bandwidth-intensive services has become a possibility. One such service is the delivery of video applications such as broadcast and interactive services. Due to network issues, including a lack of error detection on the whole frame or a lack of a reverse link, networks may not be able to guarantee zero errors in the transmission. For this reason, it is important to assess the impact of bit errors on the video stream. Since video is not well suited for study using analytical tools, we developed a simulation tool that could display and evaluate digital video streams and could also simulate a variety of radio configurations and channel models.

The research performed for this project is aimed at evaluating error correction codes on a digital video stream. Simulations were performed where MPEG-2 video streams were transmitted over communications systems using a variety of error correction codes and in an AWGN channel with and without co-channel interference. Simulation results show that there is little correlation between BER and video quality, where estimates of video quality based on BER ranged over several dB. A metric based on the error correction code's failure statistics was developed and it provides an estimate of video quality that is far tighter than that provided by BER. This metric offers a simple statistical method to predict the quality of a delivered video stream based solely on physical layer parameters.

## ***E-911 Service Location System Evaluation***

Sponsored by  
***Comcast Cellular***

Principal Investigators  
***Jeffrey H. Reed, Brian D. Woerner, Amy Bell***

Student Researchers  
***P. Max Robert, Elise Caruso***

Project Duration  
***1998-1999***

In 1996, after several well-publicized stories regarding the inadequacy of emergency service for cellular callers came to light, the Federal Communications Commission (FCC) announced its mandate for enhanced emergency services for cellular phone callers. The FCC required a phased implementation of progressively increasing emergency services in wireless 911 systems. In the final phase of E-911 implementation, to be completed by November 1, 2001, the wireless carrier must provide latitude and longitude estimates of the caller's position within an accuracy of 125 m RMS. In addition, the FCC has already asked for comments on tightened accuracy requirements, including estimates of vertical position, which might be imposed after the year 2001 deadline.

For the past several years, Comcast Cellular has been evaluating a location system based on time-difference of arrival (TDOA) technology. The system's equipment, produced by TruePosition Inc., was tested in the last half of 1998. Comcast employed Virginia Tech to assist with the testing and analysis of this system. The analysis procedure was particularly challenging given the vagueness of the FCC criterion for accuracy. Virginia Tech, Comcast, and TruePosition worked together to develop an analysis procedure that considers the impact of lost calls, the density of emergency calls, and the validity of the location measurement.

This project was split into two main parts: data collection and evaluation. The data collection entailed the development of a data collection methodology and involved assembling the system data for later evaluation. The collection methodology was developed; data collection on the test plan was performed using a combination of commercially available software and custom software written at Virginia Tech. The data was then collected in a central database using a collection and evaluation tool written for this project by researchers at Virginia Tech. Once the data was collected, the performance of the system was evaluated using a variety of metrics.

## ***Configurable and Robust Wireless Communication Nodes***

Sponsored by  
***Defense Advanced Research Projects Agency (GLOMO II)***

Principal Investigators  
***J. H. Reed, B. D. Woerner, P. A. Athanas, W. L. Stutzman, S. Midkiff, W. H. Tranter***

Student Researchers  
***P. Atinirarnit, T. Biedka, N. Correal, J. Davies, C. Dietrich, K. Dietz, R. Ertel,  
M. Hoseman, Z. Hu, S. Kim, N. Mangalvedhe, R. Mostafa, K. Phillips,  
S. Srikanteswara, M. Valenti, Y. Wu***

Project Duration  
***July 1997-September 2000***

We proposed to implement and test a breakthrough software radio that would provide robust high rate communications over long distances while maintaining a tight power budget. By reconfiguring their processing on a real-time basis, software radios offer the flexibility to implement multiple air interfaces. This capability facilitates rapid deployment and provides the capacity to adapt to hostile environments. A software radio achieves robust performance through sophisticated processing for tasks such as interference rejection, encryption, multipath rejection, and variable rate coding, which are not possible with a conventional radio design. This makes software radios ideal for high rate, multimedia communications, such as real-time video. We are currently exploring this application as a part of our research.

A major drawback of contemporary software radios is the large computational complexity and the resulting high power consumption. To overcome these problems, we have made important breakthroughs in the development of reconfigurable, computing-based radio modules for performing complex signal processing tasks. By leveraging reconfigurable processors, we can design software radios that only use the processing power necessary to accomplish the task at hand. This results in a computationally efficient radio design and implementation. Specifically, we have outlined plans for creating a new radio architecture with the flexibility and advanced features to serve the varying needs of the GloMo community. We offer the following innovations:

- New Software Radio Architecture
- Run-time Reconfigurable Computing Platform
- Robust High Performance Communication
- Virtual Testbed for Simulating Performance
- Supporting Tools

## ***Enhancing the Capacity of IMT-2000 through Turbo Coding and Smart Antennas***

Sponsored by  
***LGIC***

Principal Investigators  
***Jeffrey H. Reed, Brian D. Woerner, William H. Tranter***

Student Researchers  
***Rajesh Banarjee, Yufei Wu, Anwer Khan, Raqibul Mostafa,  
Fakhrul Alam, Yash Vasavada***

Project Duration  
***1998-1999***

There is an ongoing global effort to harmonize mobile communications standards, an effort directed toward establishing a common standard that will support seamless operation among different service providers. The International Telecommunications Union (ITU) and other similar organizations are exploring new standards and recommendations for providing a higher service quality (such as that of multimedia and fixed-user services) for mobile communications channels. Various international institutions are involved in the process of investigating and providing standards for the new IMT-2000 (International Mobile Telecommunications in the year 2000) in line with the ITU's work. Under IMT-2000, there are several proposed standards. Among them, there is a standard known as W-CDMA (Wideband CDMA) that will define the parameters for the next generation CDMA standard. MPRG is currently involved in sponsored research with LGInformation & Communication, Ltd. (LGIC) to investigate techniques for the incorporation of interference rejection capability and performance improvement in a system employing the W-CDMA standard.

The goal of this project is to enhance the capabilities of IMT-2000 by creating an adaptive array antenna and developing appropriate high performance channel coding techniques, and to export this technology to LGIC. This includes deriving new algorithms as well as simulating and analyzing the algorithms to ensure that performance goals are satisfied. This project provides the algorithm development and assessment as well as a preliminary high level design of the hardware implementations of the turbo coder and decoder. A possible continuation of this project would provide the detailed design, construction, and testing of the systems and would consider interference robust receivers as a technique for achieving improved system performance.

***Navy Collaborative Integrated Information Technology Initiative  
(NAVCIIITI)***

Sponsored by  
***Office of Naval Research***

Principal Investigators  
***K. Reifsnider, C. Bostian, J. Carroll, R. Claus, C. Gaylord, D. Hix,  
R. Kriz, R. Nance, A. Nayfeh, J. Reed, W. Stutzman***

Project Duration  
***November 1998-September 2000***

The proposed program will establish a Navy Collaborative Integrated Information Technology Initiative (NAVCIIITI) by creating an Advanced Communication and Information Technology Center (ACITC) at Virginia Tech. The program will integrate the efforts of more than sixty investigators currently under contract to the Navy by providing equipment and facilities for their effort. It will utilize the collective capabilities of NAVCIIITI to support Navy initiatives in distributed computing, integrated services training, education, information dissemination, and simulation, especially for purposes of network-centric battle management, managing and maintaining C4ISR attributes, and enhancement of the Naval intranet.

Under this program, the following will be created and developed:

- A state-of-the-art advanced communications and information technology facility with integrated IT research, education, and training activities that include collaborative R&D efforts in systems engineering, software engineering and validation, software usability, user interfaces, training applications, control systems, visualization (including a networked CAVE facility), simulation, immersive virtual environments, and fiber optic and wireless communication technologies.
- Methodologies and facilities for integrated immersive process design, management, and control environments.
- Integrated evaluation and design methods for information communication and technology to include usability, human-computer interaction, active/discovery-oriented learning, and verification and validation techniques for distributed simulation models in the context of legacy systems, interoperability, remote operation/simulation, and single processor model execution.
- Integrated software quality assessment and prediction methodologies for controlled development and maintenance through the collection, evaluation, and analysis of process and product indicators, including code indicators, document quality indicators, process indicators, and automated configuration management processes.
- Integrated communications systems and technologies to include new fiber optoelectronic devices and wireless systems, with validation and demonstration in an existing high-bandwidth regional infrastructure.



# ***Low Power and Robust Communications Using Hand-Held Smart Antennas for Receiving and Transmitting***

Sponsored by  
***Texas Instruments***

Principal Investigators  
***Jeffrey H. Reed, Warren L. Stutzman***

Student Researchers  
***Carl Dietrich, Kai Dietze, Rich Ertel, Raqib Mostofa, Bill Newhall***

Project Duration  
***1998-1999***

Smart antennas hold the promise of providing significant performance improvements in third generation handheld radios. The Mobile and Portable Radio Group (MPRG) and the Antenna Group at Virginia Tech are teamed to investigate key aspects of smart handset-antennas for Texas Instruments. This includes collecting antenna and propagation measured data, evaluating diversity and adaptive algorithms, simulating overall system performance, and quantifying basic phenomena that impact handsets with smart antennas. Since starting this project in July 1998, we have created two tools, a Handheld Antenna Array Testbed (HAAT) and a Vector Multipath Propagation Simulator (VMPS). These tools have been used along with the MPRG Antenna Array Testbed (MAAT) to gain an understanding of the propagation environment as perceived by a vector arrangement of antennas at the handset. This information has been used to predict the performance of smart antennas employed at the handset.

Preliminary measurements indicate that gains in the link budget of 3-11 dB are feasible in an indoor environment by using either smart antennas at the transmit or receive end with antenna separations of 0.17 wavelengths. Thus, substantial improvements in transmit power savings are possible for the handset.

Outdoor measurements will require the development of a wideband measurement system since frequency selective fading becomes an issue. Two wideband measurement systems are currently under construction to address the environments in which frequency selective fading becomes an issue. This measurement capability will also be used to determine the extent to which spatial and temporal diversity are synergistic.

## ***Evaluation of Voice Operated Email System***

Sponsored by  
***Crossmedia***

Principal Investigators  
***A.A. (Louis) Beex, Willard Farley***

Student Researchers  
***James Hicks, Sundar Sankaran, Pulakesh Roy, John Tilki***

Project Duration -  
***1998-1999***

Crossmedia, an interactive voice recognition company, offers a service called HandsFree email, which employs a small vocabulary voice recognition system that allows users to check their email remotely over the telephone.

To evaluate Crossmedia's system, Virginia Tech has developed a tool that models the voice quality of a myriad of wireless environments called "Mobile Email." There are three components of Mobile Email: the Audio Environment, the Audio Interference, and the Wireless Channel. Each component models a set of effects commonly detrimental to voice quality.

There are four types of Audio Environments considered in the simulation tool: "Automobile," "Hallway," "Sidewalk Café," and "Auditorium." Each simulator models the specific echoes and background noises present in that environment. For instance, the automobile environment models acoustical modes present for a single, hands-free microphone in a common sedan. A hallway models the severe echoes commonly present in a hallway. All Audio Environment models are based on measured empirical data collected by researchers at Virginia Tech.

In the second component of Mobile Email, a variety of Audio Interference types are modeled. One option, "engine, wind, and tire noise," is a common interference present in automobile environments. Another option called the "the cocktail party effect" is a common interference found in cafés and airports. "Music" is an interference type prevalent in any environment.

Finally, the third and largest component, Wireless Channel, models every part of a mobile telephone system, including vocoder, channel coding, multipath propagation, RF noise and interference, and equalization. The three most common wireless standards were considered: AMPS, IS-95, and IS-136.

Mobile Email is a comprehensive voice-quality simulation tool for the wireless environment.

# ***Selective Interference Cancellation Techniques for Enhanced Communications Throughout***

Sponsored by  
***Office of Naval Research***

Principal Investigator:  
***Brian D. Woerner***

Student Researchers:  
***Mostafa Howlader***

Project Duration  
***June 1997-September 2000***

This project focuses on the use of interference cancellation techniques for spread-spectrum communications in a battlefield environment. There are four major tasks:

- Establish criteria for selecting interfering signals to be canceled from the desired signal.
- Investigate the use of interference cancellation in conjunction with error correction coding.
- Explore the use of interference cancellation in conjunction with adaptive antenna technology.
- Determine the impact of these combined processing technologies on wireless battlefield communications.

One significant problem addressed this year was the application of interference cancellation techniques to a peer-to-peer communications environment without a centralized base station. A common challenge to military communications is to furnish personnel with the means of coordination among them in the form of data, voice and video in a secure and robust environment. Packet radio networks have been widely used for this purpose. Packet radio networks combined with spread spectrum technology can exhibit robust performance for military applications. Direct sequence spread spectrum (DS/SS) is often preferred to frequency hopped spread spectrum (FH/SS) in a cellular environment, but in a peer to peer network, precise power control is difficult, leading to near-far problems.

The performance of direct-sequence spread-spectrum (DS/SS) in packet radio networks suffers from the near-far problem. The near-far problem can be mitigated by the use of multiuser receivers. We introduced a model for peer to peer communications using simple subtractive interference cancellation techniques, which require cancellation of only a few dominant interferers. These techniques include parallel multistage interference

cancellation and successive interference cancellation. The performance of interference cancellation depends on the desired user power, the variation of interfering users' signal strength and the power of the strongest interfering signal. The system performance is evaluated for various spatial arrangements of interferers, and for different loading conditions. Simulation results were compared with the predicted analytical performances for these two subtractive interference cancellation techniques considering various factors such as amplitude estimation and partial cancellation factor.

Mostofa's results include a comparison of single user and multiuser receiver for peer-to-peer communication and a technique for allowing iterative processing of interference cancellation and error correction stages of the receiver.

### ***Publications***

- Mohammad M.K. Howlader and Brian D. Woerner, "Direct-Sequence Spread-Spectrum with Multiuser Detection for Peer to Peer Packet Radio," presented at *MILCOM '98 (Military Communications Conference)*, November 2-4, 1998, pp. 762-766.

## ***Data Fusion for Improved Location Capability***

*Sponsored by*  
**Nortel**

Principal Investigators  
**A. Bell, B. D. Woerner, J. H. Reed**

Student Researchers  
**A. Mishra, R. Reza**

Project Duration  
**June 1998 – May 1999**

In October 1996, the Federal Communications Commission (FCC) announced requirements for enhanced emergency services (E-911) for wireless systems. By October 2001, those requirements will include position estimation to within 125 m in 67% of all cases. These requirements, along with the prospect of value-added services based on position information, provides a strong incentive for investment in location technology. Although the challenge posed by the FCC's initial mandate has yet to be met, the FCC has already asked for comments on accuracy requirements of 50 m and less.

The current techniques employed in determining location include:

- Time of Arrival (TOA) measurements to determine the range of a mobile unit from multiple base stations;
- Time Difference of Arrival (TDOA) measurements which alleviate the need for precise time references between multiple base stations; and,
- Angle of Arrival (AOA) measurements using smart antennas which allow triangulation from multiple base stations.

The strengths and weaknesses of these individual techniques are well understood and each requires reception of the mobile unit's signal at multiple base stations.

Further enhancements in performance will depend on combining disparate information from multiple types of sensor measurements. Possible sources of position information include:

- TDOA measurements taken from multiple base stations;
- AOA measurements taken from one or more base stations;
- Less reliable received signal strength measurements taken from one or more base stations; and,
- Map information which may constrain the likely location of the mobile unit.

We will explore 'data fusion' techniques that effectively combine this disparate information may lead to significant improvements in overall location accuracy.

# *Applications of Iterative Decoding Algorithms*

Sponsored by  
*Bradley Fellowship Program/DARPA*

Principal Investigators  
*Brian D. Woerner*

Student Researchers  
*Matt Valenti*

Project Duration  
*1998-1999*

## *Turbo Codes for Fading Channels*

Turbo coding is a new error correction coding technique that enables power efficient transmission of digital signals. Since their introduction, numerous studies have shown that the performance of turbo codes closely approaches the capacity limit for Additive White Gaussian Noise (AWGN) channels, but understanding of turbo code performance in fading channels has progressed more slowly. The decoding algorithm for turbo codes requires knowledge of the channel conditions, and in particular knowledge of the fading amplitude for each symbol and the noise variance for each frame. Matt Valenti has developed a pilot symbol assisted modulation technique for improved performance in fading channels through iterative estimation of the pilot symbol information. The result comes within 1 dB of performance for perfect channel estimation and is significantly more effective than previous pilot symbol techniques. Matt has furthermore showed how pilot symbols can be introduced without reduction in data rate, by selective puncturing of a small number of code symbols. This puncturing has been shown to not significantly degrade performance.

## *Multiuser detection for coded TDMA cellular networks*

Several techniques can be used to improve the performance of digital Time Division Multiple Access (TDMA) cellular networks, including multiuser detection, error correction coding, and base station diversity. However, each of these techniques is usually studied independently of the others and utilizes only locally optimal solutions. In this study, the performance of TDMA systems using all three techniques (multiuser detection, error correction coding, and base station diversity) is investigated, with special attention paid to the interface among the individual algorithms. An iterative processing technique, similar to the technique used to decode turbo codes, is used to perform combined multiuser detection and channel decoding utilizing information from several base stations. Results show that by using this technique the number of cells per cluster can be greatly reduced, and in some situations universal frequency reuse may become possible for TDMA systems.

## ***Publications***

- Matthew C. Valenti and Brian D. Woerner, "Combined Multiuser Detection and Channel Decoding with Receiver Diversity," presented at GLOBECOM '98 (Global Communications Conference: Communications Theory Mini Conference), Sydney, Australia, November 8-12, 1998, pp. 137-142.
- Matthew C. Valenti and Brian D. Woerner, "Multiuser Detection with Base Station Diversity," presented at ICUPC '98 (IEEE International Conference on Universal Personal Communications," Florence, Italy, October 5-9, 1998, pp. 1189-1194.
- Matthew C. Valenti and Brian D. Woerner, "Iterative Multiuser Detection for Convolutionally Coded Asynchronous DS-CDMA," presented at PIMRC '98 (9<sup>th</sup> International Symposium on Personal, Indoor and Mobile Radio Communications), Boston, Massachusetts, September 13-16, 1998, pp. 213-217.
- Matthew C. Valenti and Brian D. Woerner, "Refined Channel Estimation for Coherent Detection of Turbo Codes Over Flat-Fading Channels," *IEE Electronics Letters*, Vol. 34, No. 17, August 20, 1998, pp. 1648-1650.

# ***Practical Implementation of Parallel Interference Cancellation Techniques***

Sponsored by  
***MPRG Industrial Affiliates***

Principal Investigators  
***Brian D. Woerner***

Student Researchers  
***Neiyer Correal***

Project Duration  
***1998-1999***

## ***Multiuser Detection***

Over the last decade, there has been a large body of theoretical research on the use of multiuser receiver for CDMA systems. In principle, such receivers offer significant improvements and in capacity and near-far resistance. Techniques with reasonable complexity include linear techniques based on decorrelation of interference sources and estimation and cancellation of interference sources. Such techniques have now matured to the point where it is reasonable to consider their integration into practical hardware applications, such as the upcoming 3G systems.

## ***Implementation Considerations***

Neiyer has selected parallel interference cancellation for special study because of its relatively low complexity, excellent performance and robustness to estimation error. He has considered practical DSP implementation of this technique and investigated a implementation issues. His accomplishments include:

- Development of a prototype DSP implementation of a CDMA receiver using parallel interference cancellation.
- Development of techniques for simplified implementation and for partitioning the algorithm within a multiprocessor DSP system.
- Demonstration of the benefits of combining parallel interference cancellation with polarization diversity.
- Investigation of the use of a partial cancellation factor to mitigate bias within a heavily loaded CDMA system.
- Development of a non-coherent implementation of parallel interference cancellation.

## ***Publications***

- Neiyer S. Correal, Steve Swanchara and Brian D. Woerner, "Implementation Issues for Multiuser DS-CDMA Receivers," *International Journal of Wireless Information*, Vol. 5, No. 3, 1998, pp. 257-279.



- Neiyer S. Correal, R. M. Buehrer and Brian D. Woerner, "A DSP-Based DS-CDMA Multiuser Receiver Employing Partial Parallel Interference Cancellation," *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 4, April 1999, pp. 613-630.
- Neiyer S. Correal and Brian D. Woerner, "Evaluation of Dual Spatial and Polarization Diversity Reception for DS-CDMA Multiuser Detection," presented at ICUPC '98 (IEEE International Conference on Universal Personal Communications, Florence, Italy, October 5-9, 1998, pp. 789-793.
- Neiyer S. Correal and Brian D. Woerner, "Enhanced DS-CDMA Uplink Performance Through Base Station Polarization Diversity and Multistage Interference Cancellation," presented at GLOBECOM '98 (IEEE Global Communications Conference), Sydney Australia, November 8-12, 1998, pp. 748-753.

# ***Implementation Plan for an Upgraded Statewide Land Mobile Radio Network***

Sponsored by  
***Virginia Department of Public Safety***

Principal Investigators  
***Brian D. Woerner, William H. Tranter, Judy Lilly***

Student Researchers  
***Fakhrul Alam, Rajesh Banerje, Inder Bhoogeravan***

Project Duration  
***May 1998 – April 1999***

The Virginia State Police currently make use of an outdated land mobile radio technology and plan to upgrade the system to a newer technology within the next few years. In planning for this upgrade, the Department of Public Safety wished to consider a number of issues including:

- Coordination of communications needs of the state police with other public safety agencies at the state and local level within the Commonwealth of Virginia.
- Provision for future data communications requirements.
- Consideration of the impact of new technologies including mobile satellite, cellular telephone, and PCS.

The MPRG worked with the University's Communication and Network Services office to develop an implementation plan for the upgrade project. As part of this study, we:

- Surveyed public safety agencies throughout the commonwealth on their communication needs
- Visited other states around the nation that were in various stages of upgrading their communication networks.
- Met with vendor representatives to discuss alternative technologies.
- Conducted propagation simulations to predict coverage of alternative technologies.

Based on this information, we developed a final report that recommended the development of a statewide shared digital land mobile radio network. Alternative cost estimates were formulated for 800 MHz and 150 MHz implementations, and comparisons of alternative technologies were made. Based on this recommendation, the Virginia General Assembly authorized funds to initiate the project in their Spring 1999 session.

VIRGINIA POLYTECHNIC INSTITUTE & STATE UNIVERSITY



# **PROJECT ABSTRACTS**

**1999**

**for the**

**MOBILE & PORTABLE RADIO RESEARCH GROUP**

**Bradley Department of Electrical & Computer Engineering**

**Virginia Polytechnic Institute and State University**

**432 NEB, Mail Code 0350**

**Blacksburg VA 24061**

**Tel: 540-231-2958**

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# ***Measurement and Modeling of Broadband Millimeter Wave Channels for Fixed and Mobile Next Generation Internet (NGI) Systems***

*Sponsored by  
HRL Laboratories LLC*

Principal Investigator  
***T. S. Rappaport***

Student Researchers  
***V. Kukshya, C. Anderson, J. Aron, H. Xu***

Project Duration  
***October 1999 – September 2001***

This project will provide HRL Laboratories with tools that allow detailed study and understanding of the design and of the performance limit of radio modems used for broadband wireless access (BWA). The project will be completed in two distinct stages.

The first stage of the project (currently in progress) involves the miniaturization of and an upgrade to the Mobile and Portable Radio Research Group's 38 GHz Channel Sounder for coherent, high-resolution data acquisition. Miniaturization efforts will be directed towards the replacement of the bulky oscilloscope, the frequency generator and the spectrum analyzer units of the channel sounder by relevant hardware and software. We are also in the process of upgrading the channel sounder to have a multipath resolution capability of about 2ns (800 MHz RF bandwidth) as opposed to the current capability of 10ns (200 MHz RF bandwidth). In the near future, the channel sounder will be redesigned to introduce an I and Q channel capability to gather the channel impulse phase response as well as amplitude power delay profiles (PDPs).

The second stage of the project is characterization of the broadband millimeter wave channel at 38 GHz for fixed and mobile NGI systems. This will involve planning and executing an extensive measurement campaign and then modeling the broadband channel using the acquired data. The improved spread spectrum channel measurement system is not only allows measurement of the small-scale channel as a function of direction and space, but it also removes the small-scale fading effects and reveals the true angle-of-arrival characteristics of propagation. The data gathered using the fully upgraded channel sounder will be used to develop statistical and site-specific models to quantify the multipath behavior of the channel as a function of weather events and vegetation, as well as small-scale fading.

# ***Measurement-Based Spatial-Temporal Channel Modeling for Handheld Multimedia Terminals***

Sponsored by  
***ITT Defense and Electronics, Inc.***

Principal Investigator  
***T. S. Rappaport***

Student Researchers  
***G. D. Durgin, V. Kukshya, C. B. Steger, E. N. Lau, J. Siew***

Project Duration  
***June 1999 – December 1999***

This project involved the collection and analysis of over 5000 wideband power-delay profile (PDP) snapshots for wideband radio channel characterization at 1920 MHz. Channel statistics were measured for the peer-to-peer network configuration, where both transmitter and receiver antennas have an elevation of 1.5m above ground. Path loss, dispersion, and angle-of-arrival statistics were measured and analyzed for a variety of outdoor and indoor transmitter and receiver locations. The tabulated data yield useful insight into receiver design and provide input into channel simulators.

A total of 12 locations (6 outdoor-to-outdoor, 3 outdoor-to-indoor, and 3 indoor-to-indoor) were measured extensively using an improved spread spectrum channel measurement system. The system is designed to position a receiver antenna precisely along a track and to rotate a directional antenna precisely on a spinning mast. The primary purpose for this precise positioning is to take multiple azimuthal sweeps of a directional antenna along a moving track so that, coupled with wideband channel sounding data acquisition, an image of the wideband mobile radio channel is measured that includes angle-of-arrival information.

## ***Presidential Faculty Fellowship***

*Sponsored by*  
*National Science Foundation*

Principal Investigators  
*T. S. Rappaport*

Student Researchers  
*G. Durgin, H. Xu, R. Skidmore, S. Mahmud, B. Walsh, W. Rios*

Project Duration \*  
*March 1996 – February 2000*

A thorough understanding of the radio propagation characteristics and appropriate channel modeling techniques are vital to the successful deployment of wireless networks. Contemporary wireless networks are designed relying on exhaustive propagation measurements, and it is not uncommon to avoid "dead zones" by overdesigning. This makes the network more expensive and inefficient operationally and spectrally. Research at Virginia Tech's Mobile and Portable Radio Research Group (MPRG) has developed promising propagation modeling techniques that use digitized building databases with topographic maps. The resulting propagation models provide prediction accuracies of signal strength, coverage, and multipath spread that are better than those reported in the literature. For example, the new modeling techniques provide signal strength predictions that are consistently within 5 dB of the actual local average at every point within the engineering complex of a college campus, and the models reliably predict dead zones due to the shadows of different buildings. Recently, models and measurement techniques for wireless local area networks (LANs) have been included in the research.

***Professional Production Services for Technical Reference Books at  
Prentice Hall***

Sponsored by  
***Prentice Hall PTR***

Principal Investigator  
***T. S. Rappaport***

Research Associates  
***A. Scharnhorst***

Project Duration  
***August 1998 – July 2000***

Prentice Hall, a world-leading publisher of technical books, seeks the expertise and services of Virginia Tech's Mobile and Portable Radio Research Group (MPRG). As Prentice Hall attempts to attract world-leading authors and develop leading educational and technical books, it wishes to team with the MPRG in the development of potential markets and a more prominent presence in the telecommunications field. By associating with the MPRG and its capable technical editing staff, Prentice Hall could have an advantage in attracting potential authors in the field of wireless and telecommunications.

# ***A Collaborative Problem Solving Environment for Modeling of Broadband Wireless Communications Systems***

*Sponsored by*  
***National Science Foundation***

Principal Investigator  
***T. S. Rappaport***

Student Researcher  
***P. T. SheethalNath***

*Project Duration*  
***August 1999 – August 2002***

There does not currently exist an integrated environment to support the collaborative design and analysis of a wideband wireless communication system. While primitive software tools exist for cellular and PCS system design, none of these tools includes models for the effects of buildings and other man-made objects. This is a key factor in determining the performance of wireless modems. The proposed system would provide the capability to design, deploy and evaluate the performance of the wireless network, efficiently taking into account the site-specific details of the area. Ray tracing techniques will be used in performing the site-specific analysis of the wireless system.

Research has previously been conducted in the Mobile and Portable Radio Research Group (MPRG) in the area of site-specific propagation prediction using ray tracing. But to make the MPRG's software tool more useful, it should have the ability to take real world data and use this data to perform site-specific propagation prediction. The Digital Elevation Models (DEM) of different cities are obtained from satellite images. This information is in the raster format. It needs to be put into a vector format to use this information for ray tracing. Also, the location of buildings and other man-made structures must be found in order to get the details of the site where propagation is being predicted. Currently work is underway to convert files from DEM (raster format) to vector format to help in using these site-specific details for propagation prediction.

The following stage of the project is to use more sophisticated models that include diffraction and transmittance to get more accurate results about the power delay profile (PDP) and the average signal-to-noise ratio at various points in the site that can then be used to design and deploy wireless networks more efficiently. There is also research in progress about how to optimize the performance of the system and how to use Recommender systems to make the computation less tedious.



## ***Combined Research Curriculum Development (CRCD)***

Sponsored by  
***National Science Foundation***

Principal Investigators  
***Theodore S. Rappaport***  
***Brian D. Woerner***  
***Jeffrey H. Reed***  
***William H. Tranter***

Project Duration  
***September 1995 – August 1999***

The Combined Research Curriculum Development (CRCD) Grant has exceeded expectations. Three courses have been developed and offered to several groups of students; these courses are "Introduction to Wireless Communications," "DSP in Communications Systems," and "Simulation of Communication Systems."

The first course "Introduction to Wireless Communications" has been offered to students at Virginia Tech several times. In addition, this course was the initial offering of wireless communications courses at the University of Missouri - Rolla. Dr. Rappaport's textbook, upon which this course is based, has become a best-seller and is used for wireless communications courses at more than 50 schools worldwide. Software modules to support this course continue to be developed and, given the number of schools that have recently begun to offer courses in wireless communications, have a vast potential audience. The CRCD grant has already provided funding for new exam and homework problems for this course since its creation.

The second course in the sequence "DSP in Communications Systems" has proven to be a very popular combined lecture/laboratory course. The hardware design experience gained in this course is unusual in the academic setting and as a result, students completing this course are heavily recruited by industry. As a result of the development of this course, a contract has been signed with Prentice Hall for a textbook on software radios.

The third course to be developed under the CRCD Grant, "Simulation of Communication Systems," has been taught four times to large classes at Virginia Tech and has also been offered a number of times at the University of Missouri - Rolla. In the spring of 1995, Professor Tranter was granted an Erskine Fellowship at Canterbury University in Christchurch, New Zealand, for the purpose of making the simulation course available to students at Canterbury.

Prentice Hall has teamed with the faculty at Virginia Tech to publish all textbooks resulting from the CRCD study. Two books have already been published dealing with the

first course. The books for "DSP in Communications Systems" and "Simulation of Communication Systems" are under contract to Prentice Hall and are nearing completion. Thus, within a short time, new textbooks written by the grantees will be available for each course developed as a part of the CRCD effort. A large number of system simulations, written in MATLAB, have been developed to support the courses forming the wireless curriculum described above. These have been assembled into a number of modules, each of which serves as a laboratory for investigating important concepts presented in one of the three courses developed as a part of the CRCD effort. These will be published by Prentice Hall as a sequence of small books, which will form the EDAPS (Examples, Demonstrations, and Application Packages for Simulation) Series. Several papers have also been published as a result of the support received for the CRCD effort. Thus, the CRCD grant has resulted in the development of a wireless curriculum of three courses that will be disseminated to other schools using papers, web pages, and, most importantly, textbooks.

# ***Signal Extraction Techniques for Overloaded Array Environments***

*Sponsored by*  
***Raytheon Systems Company***

Principal Investigators  
***R. J. Boyle, J. H. Reed, W. H. Tranter***

Student Researchers  
***Saffet Bayram, James Hicks***

Project Duration \*  
***August 1999 – January 2000***

This project investigates novel signal extraction techniques for overloaded arrays. Overloaded array processing facilitates airborne C3I operations in high interference environments. An N-element antenna array is said to be overloaded if more than N co-channel, near-equal power signals impinge on the array at the same time. In this case, spatial array processing techniques (e.g., beamforming, MUSIC, ESPRIT) break down.

An application of overloaded array processing is the airborne communication node (ACN): a high-altitude airborne receiver which can support wireless communications to large number of mobiles over a large geographical area. Such a communications link has obvious tactical applications. One fundamental problem the ACN faces is a large amount of interference. Overloaded array processing can assure a reliable communication link in hostile interference environment.

In this project, MPRG has completed a system analysis and a literature survey. The system analysis includes link budgets, signal modeling, and choice of array geometry for the ACN operating in a cellular environment. MPRG has also compiled a detailed literature survey of over 200 array processing papers. The remainder of this project, now considered Phase I of a potential two-phase project, is to implement via simulation a selected number of promising solutions to the ACN interference problem. We have earmarked certain detection techniques to investigate further in Phase II.

## ***Application of the C62xx Turbo Encoders/Decoders***

Sponsored by  
***Texas Instruments***

Principal Investigators  
***Will Ebel***

Student Researcher  
***Anwer Khan***

Project Duration  
***8/16/99-8/15/00***

The discovery of Turbo codes is one of the most important developments in coding theory in many years. Turbo codes are claimed to have the highest performance per unit complexity of any coding scheme to date. Almost every wireless and wireline standards committee is considering Turbo codes for possible adoption.

We propose to implement a serial and a parallel concatenated Turbo encoder/decoder algorithm pair on the TMS320C62xx. Our goals are three-fold: (1) to demonstrate that it is possible to implement a complete Turbo encoder/decoder algorithm, with parameters suitable for wireless applications, on this programmable DSP, (2) suggest improvements/modifications to the C62xx that will simplify the implementation or make the implementation more efficient, and (3) determine the range of Turbo code sizes (blocklength), configurations, and data rates that can be achieved. These goals will help TI identify the market potential for their programmable chips to developers of wireless communications technologies and also indicate architectural enhancements for Turbo decoder implementations.

In previous grants from TI, we have implemented and studied the practical effects of fixed-point arithmetic on Turbo decoder algorithms and have achieved coding gains with fixed-point number sizes as small as 4 bits. The potential commercial applications are abundant.

## ***Selective Interference Cancellation Techniques for Enhanced Communications Throughout***

Sponsored by  
***Office of Naval Research***

Principal Investigator:  
***Brian D. Woerner***

Student Researchers:  
***Mostafa Howlader***

Project Duration  
***June 1997-September 2000***

This project focuses on the use of interference cancellation techniques for spread-spectrum communications in a battlefield environment. There are four major tasks:

- Establish criteria for selecting interfering signals to be canceled from the desired signal.
- Investigate the use of interference cancellation in conjunction with error correction coding.
- Explore the use of interference cancellation in conjunction with adaptive antenna technology.
- Determine the impact of these combined processing technologies on wireless battlefield communications.

One significant problem addressed this year was the application of interference cancellation techniques to a peer-to-peer communications environment without a centralized base station. A common challenge to military communications is to furnish personnel with the means of coordination among them in the form of data, voice and video in a secure and robust environment. Packet radio networks have been widely used for this purpose. Packet radio networks combined with spread spectrum technology can exhibit robust performance for military applications. Direct sequence spread spectrum (DS/SS) is often preferred to frequency hopped spread spectrum (FH/SS) in a cellular environment, but in a peer to peer network, precise power control is difficult, leading to near-far problems.

The performance of direct-sequence spread-spectrum (DS/SS) in packet radio networks suffers from the near-far problem. The near-far problem can be mitigated by the use of multiuser receivers. We introduced a model for peer-to-peer communications using simple subtractive interference cancellation techniques, which require cancellation of only a few dominant interferers. These techniques include parallel multistage interference

cancellation and successive interference cancellation. The performance of interference cancellation depends on the desired user power, the variation of interfering users' signal strength and the power of the strongest interfering signal. The system performance is evaluated for various spatial arrangements of interferers, and for different loading conditions. Simulation results were compared with the predicted analytical performances for these two subtractive interference cancellation techniques considering various factors such as amplitude estimation and partial cancellation factor.

Mostofa's results include a comparison of single user and multiuser receiver for peer-to-peer communication and a technique for allowing iterative processing of interference cancellation and error correction stages of the receiver.

### ***Publications***

- Mohammad M.K. Howlader and Brian D. Woerner, "Direct-Sequence Spread-Spectrum with Multiuser Detection for Peer to Peer Packet Radio," presented at *MILCOM '98 (Military Communications Conference)*, November 2-4, 1998, pp. 762-766.

# ***Measurements and Simulations of Smart Base Station Performance for Various Propagation Environments***

Sponsored by  
**Metawave**

Principal Investigators  
**Warren L. Stutzman, Jeffrey H. Reed, Dennis Sweeney**

Student Researchers  
***Byung-Ki Kim***

Project Duration  
***March 1999-February 2001***

The meaning of 'smart' varies from simple diversity combining to adaptive algorithm implementations in base station antenna systems. Switched-beam antennas have been studied in cellular applications to increase signal power and reduce interference with adjacent cells. Recently a smart antenna system with switched-beam antennas has been deployed at Virginia Tech to investigate methods to increase channel capacity by traffic load balance with the sector synthesis techniques. Switched beam antennas also can be applied to the angle diversity implementation.

Diversity techniques are used at the base station to overcome multipath fading. Of the diversity options, spatial diversity is the least attractive because it requires a second antenna subsystem. Indoor and outdoor measurements of space, polarization, and angle diversity for a cellular smart base station operating in urban environments were preformed using the experimental testbed under the identical conditions. Measurements with three orientations of the mobile unit antenna were preformed at various locations and distances ranging from 150 m to 5 km from the eight channel smart base station testbed experienced with urban picocell, microcell, and macrocell. Diversity gains for the three diversity antenna schemes are compared and relative performance comparisons are made. Doppler effect measurements with a vehicle moving at highway speeds and other interesting initial measurements are also being examined.

Research topics also include downlink transmit diversity, fully adaptive antennas, comparison of fully and quasi-adaptive solutions, tracking of mobile user location, wideband signal implementations, and space-time processing. Both measurements and simulation approaches will be used. This research will be valuable in determining what kind of smart antenna system should be deployed for the given propagation environments.

# ***Configurable and Robust Wireless Communication Nodes***

Sponsored by  
***Defense Advanced Research Projects Agency (GLOMO II)***

Principal Investigators  
***J. H. Reed, B. D. Woerner, P. A. Athanas, W. L. Stutzman, S. Midkiff, W. H. Tranter***

Student Researchers  
***P. Atinirarnit, P. Balister, T. Biedka, N. Correal, J. Davies, K. Dietz, R. Ertel, R. Gozali, M. Hoseman, Z. Hu, Y. Jemibewon, S. Kim, T. Lin, N. Mangalvedhe, R. Mostafa, J. Neal, K. Philips, B. Pucket, S. Srikanteswara, N. Smavatkul, M. Soni, M. Valenti, Y. Wu***

Research Associate and Research Faculty  
***C. Dietrich, R. Boyle***

Project Duration  
***July 1997-September 2000***

We proposed to implement and test a breakthrough software radio that would provide robust high rate communications over long distances while maintaining a tight power budget. By reconfiguring their processing on a real-time basis, software radios offer the flexibility to implement multiple air interfaces. This capability facilitates rapid deployment and provides the capacity to adapt to hostile environments. A software radio achieves robust performance through sophisticated processing for tasks such as interference rejection, encryption, multipath rejection, and variable rate coding, which are not possible with a conventional radio design. This makes software radios ideal for high rate, multimedia communications, such as real-time video. We are currently exploring this application as a part of our research.

A major drawback of contemporary software radios is the large computational complexity and the resulting high power consumption. To overcome these problems, we have made important breakthroughs in the development of reconfigurable, computing-based radio modules for performing complex signal processing tasks. By leveraging reconfigurable processors, we can design software radios that only use the processing power necessary to accomplish the task at hand. This results in a computationally efficient radio design and implementation. Specifically, we have outlined plans for creating a new radio architecture with the flexibility and advanced features to serve the varying needs of the GloMo community. We offer the following innovations:

- New Software Radio Architecture
- Run-time Reconfigurable Computing Platform
- Robust High Performance Communication
- Virtual Testbed for Simulating Performance
- Supporting Tools



# ***Low Power and Robust Communications Using Hand-Held Smart Antennas for Receiving and Transmitting***

Sponsored by  
***Texas Instruments***

Principal Investigators  
***Jeffrey H. Reed, Warren L. Stutzman***

Student Researchers  
***Carl Dietrich, Kai Dietze, Rich Ertel, Raqib Mostofa, Bill Newhall,  
Uwe Ringel, Kazi Zahid, Ramesh Chembil Palat***

Project Duration  
***1998-2000***

Smart antennas hold the promise of providing significant performance improvements in third generation handheld radios. The Mobile and Portable Radio Group (MPRG) and the Antenna Group at Virginia Tech are teamed to investigate key aspects of smart handset-antennas for Texas Instruments. This includes collecting antenna and propagation measured data, evaluating diversity and adaptive algorithms, simulating overall system performance, and quantifying basic phenomena that impact handsets with smart antennas. Since starting this project in July 1998, we have created several tools, a Handheld Antenna Array Testbed (HAAT), Vector Impulse Response (VIPER) Testbed, and a Vector Multipath Propagation Simulator (VMPS). These tools have been used along with the MPRG Antenna Array Testbed (MAAT) to gain an understanding of the propagation environment as perceived by a vector arrangement of antennas at the handset. Construction of a Smart Transmit Array is underway. This information has been used to predict the performance of smart antennas employed at the handset.

Preliminary measurements indicate that gains in the link budget of 3-11 dB are feasible in an indoor environment by using either smart antennas at the transmit or receive end with antenna separations of 0.17 wavelengths. Thus, substantial improvements in transmit power savings are possible for the handset.

To exploit the potentially large reduction in transmit power adaptive feedback algorithms to control The Smart Transmit antenna have been developed, simulated, and are being incorporated on The Smart Transit Array Testbed.

## ***Broadband Channel-Adaptive Radio Modem for NGI Network Extension and Access***

Sponsored by  
***Hughes Network Systems***

Principal Investigator  
***Jeffrey H. Reed***

Student Researchers  
***Arif Hannan, Max Robert***

Project Duration  
***October 1999 – September 2001***

Broadband Wireless is now one of the most exciting fields in Wireless Communication. The Mobile and Portable Radio Research Group (MPRG) at Virginia Tech, UCLA and Hughes Network Systems (HNS) are working with HRL Laboratories on the project of "Gigabit/s Wireless Technology for the NGI Network Extension". In this project MPRG is working towards the design of the Broadband Channel-Adaptive Radio Modem. The Task includes measurement and modeling of the RF channel at 38 GHz and developing and optimizing the design of the reconfigurable channel-adaptive radio modems through simulation. This is an important thrust of the project because it addresses the performance limits for broadband wireless access, in terms of data transport capability for the NGI network extension under realistic commercial or tactical deployment conditions.

The performance of any communication system, particularly broadband systems, requires a detail understanding of the RF channel in which it must operate, knowledge of the channel will determine the combination of modulation, diversity, equalization and coding required to optimize the capacity and quality (bit error rate) of broadband system. Hence statistical and site specific models for the broadband, millimeter wave will be developed and integrated into the simulation tool (a task under Ted Rappaport's direction). The simulation tool will conduct a feasibility study on reconfigurable channel-adaptive radio modem as a potential solution for high reliability access to the NGI network (task under Jeff Reed's direction). The reconfigurable channel-adaptive radio modem can be envisioned as an array of elementary radio modems that aggregates multiple frequency division multiplexed (FDM) channels. Each channel is chosen by a frequency band selection processor that picks the set of frequencies by monitoring channel conditions. The drawback of such a system that uses multicarrier transmission is the requirement of a highly linear RF front end because of their strong envelope fluctuation. If this requirement is not met, out of band radiation level could be too high. In order to estimate the effects of a nonlinear amplifier at the front-end of a multicarrier wideband link, nonlinear amplifier models have been developed and incorporated in the simulation tool. The effects that the simulation is expected to model are: spectral re-growth with a nonlinear RF front end, adjacent channel interference, bit/cell/frame error rate, maximum number of allowable channels, design compensation for non-linearity. Currently efforts are underway to develop a method that will reduce the peak to mean power ratio of a multicarrier signal relaxing the dynamic range requirement of the RF front end.

# **MPRG Publications – 1997**

## **Technical Reports**

“Fixed-Point Implementation of a Multistage Receiver,” Rick A. Cameron and Dr. Brian D. Woerner, Ph.D. Dissertation, MPRG-TR-96-33, January 13, 1997.

“Robust GMSK Demodulation Using Demodulator Diversity and BER Estimation,” MPRG-TR-97-01, Jeffery D. Laster and Dr. Jeffrey H. Reed, Ph.D. Dissertation, February 1997.

“Evaluation of Repeaters for CDMA Cellular and Personal Communications Systems,” MPRG-TR-97-03, Naveen Kommareddi, Muhammad Aatique and Dr. Brian D. Woerner, Technical Report prepared for Repeater Technologies, Inc., March 1, 1997.

“Evaluation of Repeaters for CDMA Cellular and Personal Communications Systems,” MPRG-TR-97-04, Naveen Kommareddi, Muhammad Aatique and Dr. Brian D. Woerner, Executive Summary prepared for Repeater Technologies, Inc., March 1, 1997.

“Novel Adaptive Array Algorithms and Their Impact on Cellular System Capacity,” MPRG-TR-97-05, Paul Petrus and Dr. Jeffrey H. Reed, Ph.D. Dissertation, March 1997.  
“Handoffs in Cellular Systems: A Tutorial,” MPRG-TR-96-35, Nishith Tripathi and Dr. Jeffrey H. Reed, Technical Report, November 1996.

“A New Class of Fuzzy Logic Based Adaptive Handoff Algorithms for Enhanced Cellular System Performance,” MPRG-TR-97-06, Nishith D. Tripathi, Dr. Jeffrey H. Reed and Dr. Hugh VanLandingham, Technical Report, April 1997.

“An Adaptive Handoff Algorithm Using Neural Encoded Fuzzy Logic System,” MPRG-TR-97-07, Nishith D. Tripathi, Dr. Jeffrey Reed and Dr. Hugh VanLandingham, Technical Report, April 1997.

“An Adaptive Direction Biased Fuzzy Handoff Algorithm With Unified Handoff Candidate Selection Criterion,” MPRG-TR-97-08, Nishith D. Tripathi, Dr. Jeffrey H. Reed and Dr. Hugh VanLandingham, Technical Report, April 1997.

“Interference Rejection for AMPS Using Time Dependent Adaptive Filtering and Model-Based Demodulation,” MPRG-TR-97-09, Wen-Chun Ting and Dr. Jeffrey Reed, Masters Thesis.

“Path Loss and Penetration Loss Measurements in and Around Homes and Trees at 5.85 GHz,” MPRG-TR-97-10, Greg Durgin, Hao Xu and Dr. Theodore S. Rappaport, Technical Report, June 1997.

"An Investigation of Carrier Recovery Techniques for PSK Modulated Signals in CDMA and Multipath Mobile Environments," MPRG-TR-97-11, Steven P. Nicoloso and Dr. Jeffrey H. Reed, Masters Thesis, June 1997.

"Enabling Technologies for MayDay Systems," MPRG-TR-97-12, MPRG and Center for Transportation Research, Technical Report, May 21, 1997.

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